EFFECTS OF EROSION ON SOIL QUALITY AND PRODUCTIVITY OF A FIELD NEAR SASKATOON

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ABSTRACT

Soil erosion has been identified as a major contributor to soil degradation on the Prairies. An 84 ha cultivated watershed near Saskatoon was selected to study the variability in erosion and deposition. ^{137}Cs deposited mainly in the early 1960's was used as a tracer for soil movement. Soil erosion ranged from 35 t/ha/yr in small tributaries to the main channel, to 4 t/ha/yr or less on upper slope areas which occupied 60% of the area. High rates of soil deposition were found in upland depressions and in the main channel. The net soil loss from the basin was 2340 t or about 1 t/ha/yr. Seventy to 80% of the lost soil was retained ahead of a dam in the coulee leaving the field. It is estimated that the eroding areas of the field (approx. 77 ha) suffered an organic C loss of 275 t from the early 1960's to mid 1980's. Preliminary estimates indicate that about 215 t of organic C were deposited in the upland depressions and the main channel inside the field boundaries. Estimates of the organic C trapped in the coulee are in the order of 50 to 90 t. Further sampling will be needed to resolve the discrepancy between estimates of organic C lost from the field, and organic C trapped in the coulee. Based on approximate relationships between soil depth and yield potential, it is expected that the production of about one-quarter of the eroding area is adversely affected by erosion when other growing conditions are good.

INTRODUCTION

The first reports of soil erosion appeared soon after the initial breaking of the native prairie. Although concerns about the impact of erosion on soil productivity arose as early as the 1940's (Neatby, 1941), it wasn't until 1961 that Ripley et al. (1961) produced a generalized erosion map for Canada and provided some estimates of the effects of erosion on productivity. In the same year, Johnson (1961) provided more detailed information for Western Canada. Johnson (1961) points out that in the assessment of regional erosion it was often difficult to distinguish between land that has eroded, is eroding or that is potentially erodible, or to separate areas of moderate and severe erosion. More recently, PFRA (1983) and the Science Council of Canada (1986) have provided estimates of soil erosion and its cost to the farmers in Western Canada.

The estimates of soil loss made in the early 1980's by PFRA (1983) are extrapolated from U.S. data which appear to be largely based on prediction equations. PFRA's estimate of the economic impact of this soil loss ($350 million per year for the prairie provinces) was based on a US study which concluded that 1 inch of topsoil loss reduced wheat yields by approximately 1.5 bu/acre. The Science Council of Canada (1986) estimated that the annual cost of soil erosion was about $430 million. Neither of the two studies appears to have looked at deposition of soil within the field, or at the off-site fate and effect of the eroded sediment.

This study was conducted to provide a detailed assessment of soil losses and gains in a cultivated field since the early 1960's, i.e. during a period in which modern agricultural practices were in effect. An attempt is also made to relate soil movement to losses and gains of organic C since the latter is an important factor in soil quality, and to provide some estimate of the effects of this erosion on productivity of the field.

METHODS

The study area is located east of Saskatoon and covers an area of 84 ha, mainly in NE15-36-4-W3. The area was selected since it had been previously used by the Saskatchewan Research Council in studies on runoff and snow redistribution. A detailed topographic map of the area was available. The cultivated part of the enclosed basin consists of light to medium-textured Dark Brown soils (mainly Elstow, Bradwell and Scott Association). The topography ranges from roughly undulating to gently rolling and is described as moderately hummocky with frequent depressions. The main drainage channel exits into a grassed runway, and from there in a coulee. A dam was constructed across the coulee in the late 1940's or early 1950's.

Initially the cultivated basin was sampled using 85 grid points established by the Saskatchewan Research Council. Since the grid sampling provided very few samples for upland depressions and the main channel, additional samples were collected from short transects across these features. At each of the sampling sites, two cores were taken and composited for subsequent analysis for ^{137}Cs, organic C, and bulk density. A horizon thickness and depths to carbonates were recorded. To trace the fate of the soil that was lost from the cultivated field, approximately 40 samples were taken from the grassed runway, the coulee and the pond before the dam.

The samples were analyzed for ^{137}Cs and soil erosion and/or deposition since the early 1960's in the cultivated field were calculated using the methods described by de Jong et al. (1983). In the runway and gully area, two different methods were used to provide estimates of soil deposition. Organic C was measured by the dry combustion or by the Walkley-Black method.

RESULTS

Soil Redistribution

Net soil losses varied widely over the approximately 25-year measuring period, ranging from losses of over 1000 t/ha to gains of nearly 3000 t/ha. To assist in the interpretation of the net soil erosion values, the topography was used to subdivide the field into seven landscape units. Each landscape unit is uniquely defined by its position in the basin and the shape of its surface. Table 1 shows the net soil erosion rates associated with each of these groupings. Four major erosion groups emerge. Approximately 93% of the cultivated area is losing soil with the highest rates of soil loss (over 20 t/ha/yr) occurring in tributaries to the main channel. The midslope and swale positions, which occupy approximately 30% of the cultivated area, lose soil at rates between 4 and 20 t/ha/yr. The crest and level upland areas, occupying 60% of the basin, lose soil at rates at 0 to 4 t/ha/yr. The main channel and all of the upland depressions are sites of soil gain, with deposition at rates over 40 t/ha/yr.

Table 1. Mean net soil erosion for different landscape units in the cultivated basin over approximately 25 years.

Unit	Area		Net erosion†	
	ha	%	10^3 ton	ton/ha
	Highest erosion rate (over 20 t/ha/yr)			
Tributary	1.1	1	1.0	900
	Intermediate erosion rate (4-20 t/ha/yr)			
Swale	9.1	11	1.2	130
Midslope	16.1	19	3.5	220
	Lowest erosion rate (0-4 t/ha/yr)			
Crest	19.6	23	1.4	70
Level	31.5	38	3.2	100
	Deposition			
Depression	5.4	6	-6.4	-1200
Main channel	0.9	1	-1.5	-1600

†Negative numbers indicate deposition

The higher rates of soil erosion in the tributaries, swales and midslope positions, suggest that water erosion is the main soil-transporting agency within the basin. Saskatchewan Research Council's runoff monitoring program in the late 1960's and early 1970's indicated that flow in the main channel was confined to the spring melt runoff period (Hall and Langham, 1970; Lakshman, 1973). Signs of runoff and erosion in response to heavy summer rainfall events were occasionally observed, but the runoff did not reach the weir in the grassed runway. Thus, runoff events during the growing season and fall move sediment into the depressions and the main channel, while only spring melt water would move soil from the cultivated part of the basin. The sediment carried out of the basin would consist of materials picked up from the main channel, and possibly material that was eroded from upslope and carried down the channel. Soil losses on the uplands and crests could be due to a combination of cultivation, wind erosion and possibly water erosion. One study, using the wind erosion equation, has estimated that the soil loss by wind erosion in the Dark Brown soil zone might be in the order of 1.5 t/ha/yr (Environmental Applications Group Limited, 1982).

Combining the net erosion rates for each landscape element with their aerial extent indicates that the cultivated part of the basin has lost approximately 2300 t of soil since the early 1960's, i.e. 1.1 t/ha/yr. Soil gain in the grassed runway, coulee and pond area was calculated by two methods. In the first method we assumed that the depth of the maximum ^{137}Cs concentration coincided with the original surface in the early 1960's, and that any soil above this depth would be from deposition. This approach worked well in the ponded area where the core samples were segmented into 5 cm layers, but was less satisfactory in the runway and coulee where the cores were segmented into 10 cm increments. Each core was then combined with a cross-sectional area of the channel to give the total amount of deposition. For the area between the cultivated field and the dam, the total soil deposition was estimated to be approximately 1500 t. In the second method, we subtracted 10 cm (^{137}Cs in natural systems was usually confined in the 0-10 cm layer in studies by de Jong et al. (1983)) to estimate the volume of soil deposited. This method is similar to that used in cultivated fields and indicated a total deposition of approximately 1900 t. These estimates indicate that between 70 and 80% of the soil that was lost from the cultivated field was redeposited in the area before the dam. The soil that was not accounted for, approximately 600 t, could have been lost by wind erosion; if so, this would give an average wind erosion rate of 0.3 t/ha/yr for the whole cultivated field or 0.5 t/ha/yr for the upland and crest areas.

Organic C Balance

Organic C losses from the eroding areas, calculated using the mean erosion rates in Table 1 and the organic C content of the A horizons measured in the mid-80's, amounted to about 220 t (Table 2). By the same method it was estimated that the depressions and main channel gained approximately 215 t of organic C. Hence, there would have been a negligible net loss of approximately 5 t of organic C from the cultivated field. As indicated above, around 1700 t of soil were recovered in the area between the field boundary and the dam. The deposits had an average organic C content of approximately 4%, giving a total organic C deposition of about 70 t, i.e. much higher than the loss calculated for the whole field. The discrepancy between the estimate of organic C lost from the cultivated field (5 t) and the amount recovered in the gully and pond area (70 t) could be due to a number of factors.

Table 2. Tentative organic C balance over a period of about 25 years†.

Landscape units	Soil loss 10^3 tons	Organic C %	Organic C loss tons
Tributary	1.0	2.4	24
Swales, midslope	4.7	2.0	96
Crests, level	4.5	2.2	98
Depressions, main channel	-7.9	2.7	-215

†Negative numbers indicate gains

The calculation in Table 2 overlooks two major factors: enrichment of the sediment compared with the source area, and possible change in quality of sediment during the 25 year period as organic C in the topsoil decreased. The enrichment of the sediment compared to the source area is clearly demonstrated by the fact that the average C content in the surface horizons of the depressions and main channel is in the order of 2.7% while the areas that are contributing, i.e. tributaries, swales, midslope, crest and level areas, have organic C contents of 2 to 2.4% (Table 2). A second example of enrichment is evident in the main channel sediments which have an organic C content of 2.8% versus the approximately 4% organic C in the sediments in the coulee. If one assumes that the average organic C content of the depressions and main channel is typical for the sediment originating on the uplands, and for the material lost to the atmosphere by wind erosion, then an alternative C balance can be derived as shown in Table 3. This balance indicates approximately 16 t of organic C lost to the atmosphere, and 259 t of organic C delivered to the main channel and depressions. The actual gain of C in the main channel and depressions was only 215 t, suggesting a net loss of 44 t of organic C from the main channel to the coulee. The data suggested a net export of 70 t of organic C to the coulee through the movement of 1700 t of main channel soil enriched from 2.7 to 4% in organic C. Thus there is still a small discrepancy between the two estimates of organic C loss from the field (45 t versus 70 t) which might be due to changes in soil quality in the cultivated field over the 25 year period.

Table 3. Alternative organic C balance†.

	Soil loss 10^3 tons	Organic C %	Organic C loss tons
To the atmosphere			
crest, level	0.6	2.7	16
Water erosion in the basin			
1. Eroded			
crest, level	3.9 }		
midslope, swale	4.7 }	2.7	259
tributary	1.0 }		
2. Deposited			
depression,			
main channel	7.9	2.7	215
Water erosion from basin			
main channel	1.7	4.0	68

†Based on enriched sediment

Because of continuing erosion, the organic C concentrations in the surface soils in the eroding part of the cultivated field are likely to have decreased over the last 25 years. Thus the values shown in Table 2 are probably lower than those that were in effect in the early 1960's and the loss of organic C from the eroding areas shown in Table 2 was probably underestimated. A similar effect may have also occurred in Table 3. Although the organic C concentrations varied widely from core to core, in about half of the cores taken from the pond area the highest organic C concentration was observed at some depth below the surface. This might indicate that the organic C content of the cultivated field gradually decreased over time. Interpretation of the core data is difficult due to the complex deposition pattern in the gully and pond, and the fact that different parts of the cultivated field may contribute to snowmelt runoff in different years and thus will affect the quality of the sediment.

Impact of Soil Erosion on Productivity

There is very little information on the impact of soil erosion on soil productivity. Often a linear relationship between thickness of topsoil and yield has been used (PFRA, 1983; Rennie, 1985). Daniels et al. (1987) have indicated some of the limitations on past research regarding the effect of soil depth on soil productivity. Innovative Acres data (to be discussed by Weisensel et al., 1989) and the data of Dormaar et al. (1986) clearly show that there is a strong interaction between the yield response to soil depth, and the amount of water available to the crop. The effect of limited soil depth is more pronounced under wet than under dry conditions. The results of Dormaar et al. (1986), expressed as a Mitscherlich type of equation, suggest that no yield advantage is gained from soil thicknesses in excess of 35 to 40 cm (Fig. 1). The relationship between relative yield and soil depths can be expressed by the equation:

$$\frac{Y}{Y_{MAX}} = 1 - 0.8\, e^{-0.06X} \qquad [1]$$

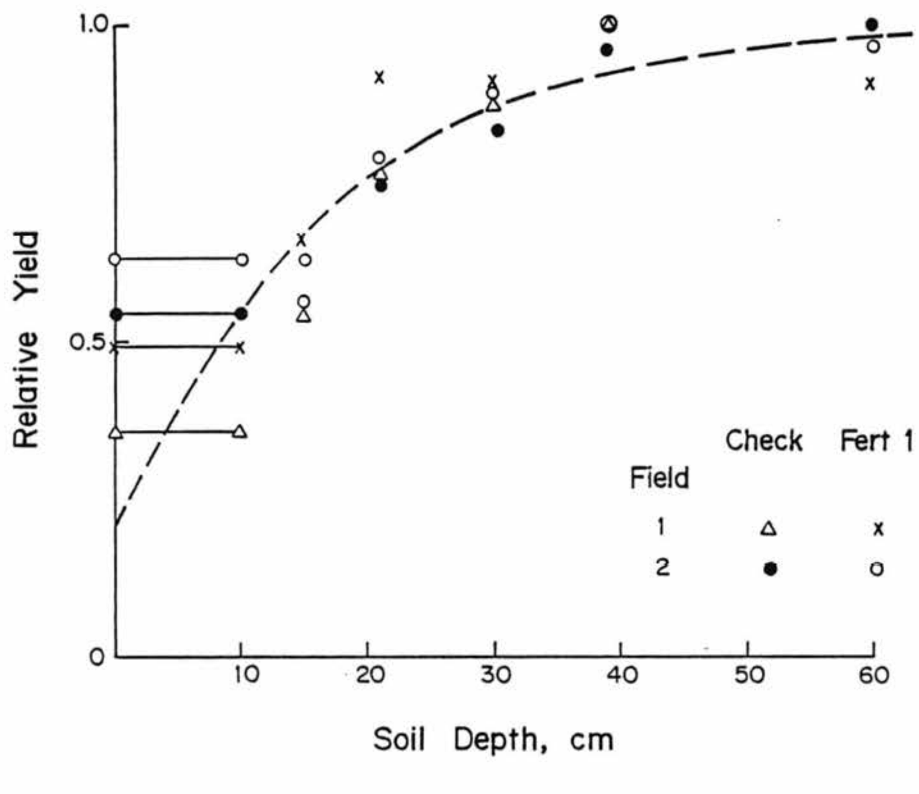

Figure 1. Effect of soil depth on yield (adapted from Dormaar et al., 1986).

where Y = actual yield; Y_{MAX} = maximum yield; X = soil depth, cm. Equation [1] is based on average yields for six crops of wheat on fallow grown in two fields with various depth of cut-and-fill 10 to 20 years earlier. The data points represent the unfertilized and low (normal) fertilizer plots. Similar conclusions can be drawn from Innovative Acres data of individual square meter yield samples plotted against solum depths for different levels of total water use (Fig. 2). Only the data for the highest and lowest total water use are shown and the curve fitted according to Eq. [1] is superimposed. Figure 2 suggests that Eq. [1] may well overestimate the effect of soil depth on yield under conditions typical of those in farmer-managed fields.

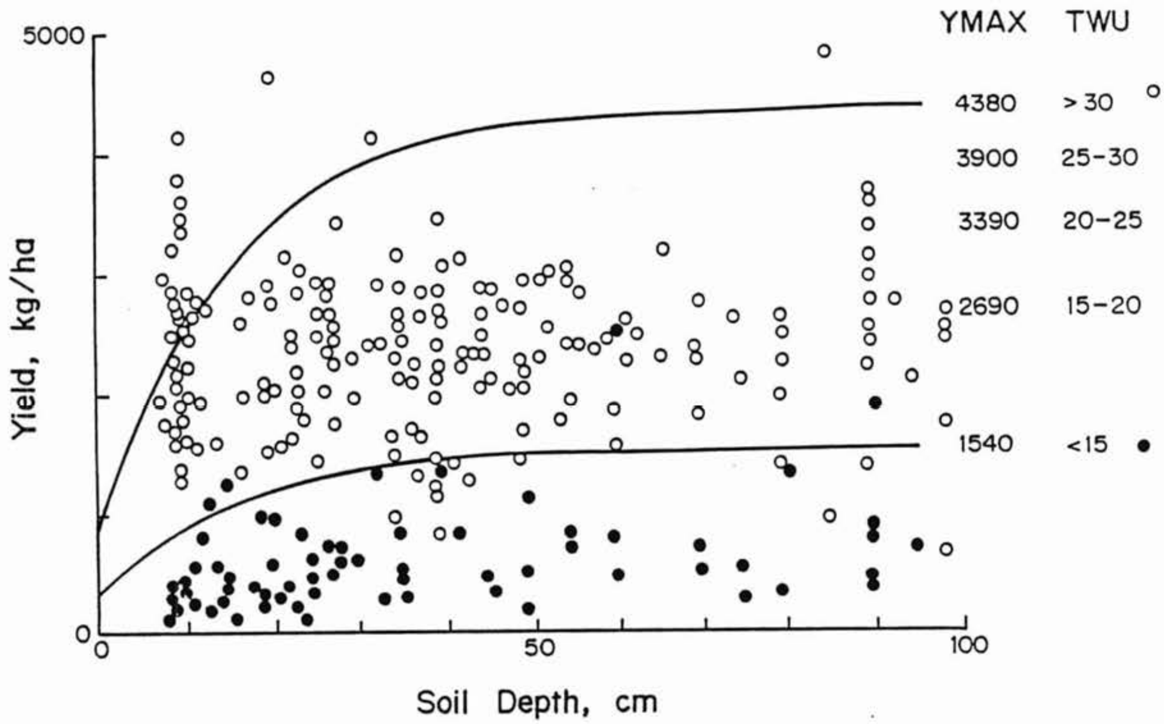

Figure 2. Effect of soil depth and crop water use (TWU in cm) on yield (Innovative Acres data).

Soil thickness in the cultivated field varied with landscape positions. The largest depths to carbonates were observed in the wetter landscape units and the thinnest soils occurred on the upper slope positions (Table 4). On average, all landscape elements were above the critical soil depth of about 30 cm. An examination of the actual distribution of soil depths (Fig. 3) indicates that approximately one-third of the field has solum thicknesses of less than 30 cm. From the solum data it would appear that past erosion has not yet significantly affected overall production in the field, but it should be realized that all changes have been negative: where soil has been lost the productivity has decreased and where soil has been gained there is no expectation of increased productivity. The thinnest soils occur on the midslope position (Table 4) where the erosion rate is nearly 10 t/ha/yr (Table 1). Erosion at this rate would reduce the soil thickness by approximately 1 cm in every 20 years, and it would take approximately 100 years before the critical soil depth of 30 cm would be reached. This calculation is dangerous as there is a negative correlation between soil erosion rate and solum thickness.

Table 4. Depth to lime on different landscape units.

Unit	Depth (cm)	
	Mean	SD
Level	38	16
Crest	38	19
Midslope	37	25
Swale	45	29
Tributary	55	33
Main channel	73	33
Depressions	79	31

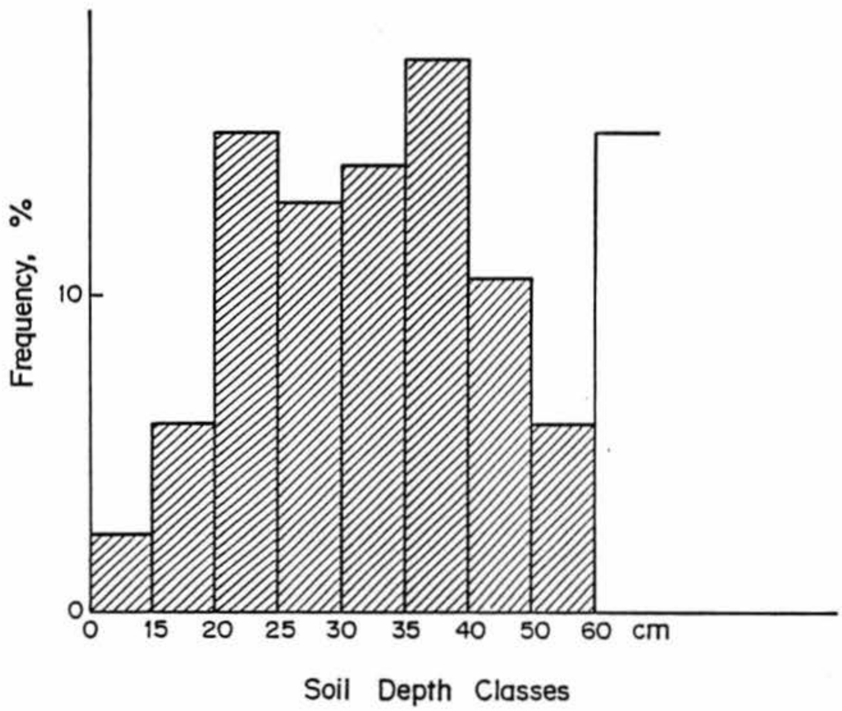

Figure 3. Frequency distribution of soil depth.

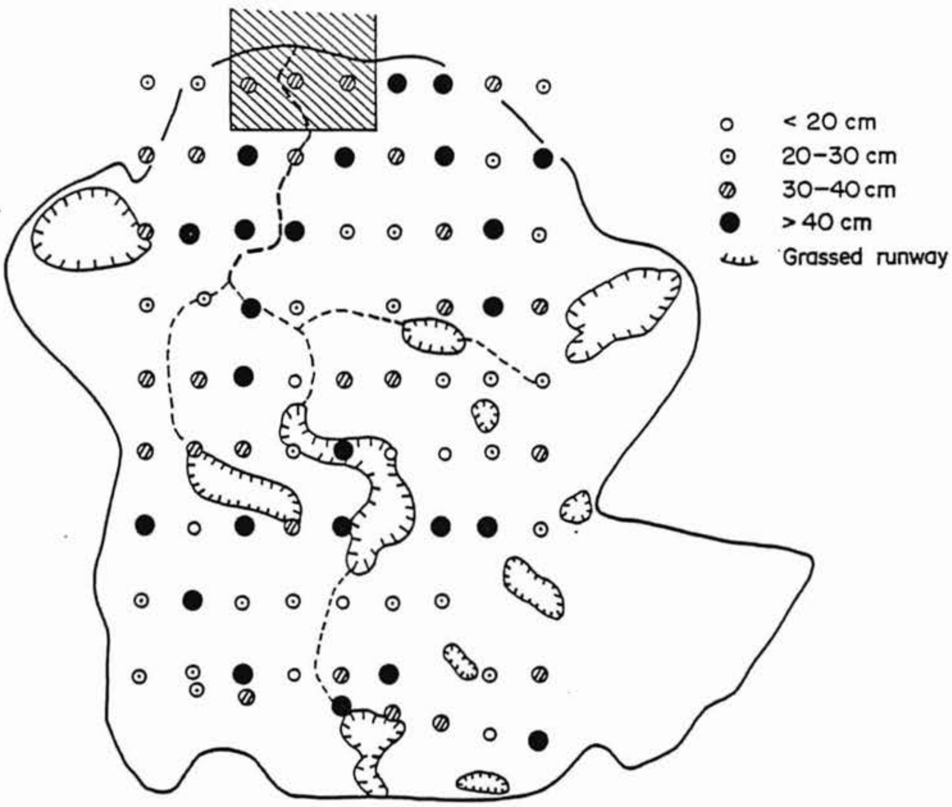

Figure 4. Variation in soil depth in the field.

A point often overlooked in considering the effect of erosion on productivity is the increase in soil variability that results, and the effect that this may have on the economic viability of the farming operation. Dealing with soil erosion and managing a field would be much easier if all erosion were confined to one part of the field rather than scattered throughout. Figure 4 indicates the location of the sites that were sampled as part of the initial grid and the soil thickness at each of those. Often thin soils or soils of moderate thickness (20 to 30 cm) occur side-by-side with areas of very deep soils. It is difficult to see how a farmer could manage these areas differently to minimize erosion and to maximize productivity. In this particular field the problem is further compounded by the fact that that the main drainage channel runs from the east to the west through the middle of the field.

CONCLUSIONS

Soil erosion and deposition were highly variable within the cultivated field. Soil deposition occurred in upland depressions and the main channel which occupied about 7% of the basin. The highest rates of erosion occurred in the tributaries to the main channel, followed by the swales and lower slopes adjacent to them. Over the 25 period the basin lost approximately 1 t soil/ha/yr, most of which was recovered in the grassed runway, coulee and pond area in the coulee. It also appears that most of the organic C lost by the field can be found back in the deposition area in the coulee.

The results of several studies suggest that the relationship between yield and soil depths is not linear and depends strongly on water supply. Under optimum growing conditions, soil depths less than 25 to 30 cm may become limiting to yields in the Dark Brown soil zone. More research is necessary on establishing the exact relationship between soil depth and yield, and the effect of increased variability due to soil erosion on the economics of production of a field.

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